Sensing and Autonomy for Riverine Vessels

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LONG-TERM GOALS

The principal goal of this project is to develop the technology and algorithms that will enable an unmanned surface vehicle (USV) to operate fast and autonomously in unknown riverine environments, including tropical rivers. Robust autonomy requires that the USV senses the surface and subsurface environments, discriminates waterways that are navigable from those that are not, indentifies stationary and moving obstacles, including other vessels, and then optimally plans and re-plan a route in real-time. Since speed is a vessel's principal defense, all of these tasks must be done as efficiently as possible to ensure successful operation at the greatest possible speed. This project is tightly coordinated with collaborators at the Naval Postgraduate School (NPS) whose work is conducted under a related project.

OBJECTIVES

Specific objectives for VT and NPS during 2011 reported herein are

1. Develop a sparse topological representation for a riverine system suitable for fast planning over very large areas.
2. Development of a generalized sonar mount so that our autonomy and sensing package can be mounted on most riverine vessels.
3. Development of a feedback control architecture that is suitable for the full operating envelope of a riverine vessel, including sternward motion.

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4. Development of a method for computing dynamically feasible trajectories that include sternward motion.

APPROACH

We seek to develop a sensing and autonomy package that can be deployed on a variety of small vessels. Thus our activities are focused on the development of sensing strategies, and guidance and control algorithms, rather than on the development of a specific USV platform. Our goal is to operate quickly in large areas for which existing maps are inaccurate. To do so, we must address the following

1. Guidance: Guidance algorithms must be suitable for extremely large and poorly mapped riverine environments. Furthermore, they must meet real-time computational contraints.
2. Dynamics and control: Fundamental principals for control of shallow-draft riverine vessels are sought. The challenge being development of a control architecture that is suitable for the entire operating envelope of a USV, including sternward motion.
3. Vessel integration: Because we seek to deploy our sensing and autonomy package on *any* riverine vessel, we are developing generalized mounting systems for our sensors. Our biggest effort has been directed toward development of a new generalized sonar mount.

WORK COMPLETED

Topological map of riverine environments for fast planning

In previous work, we had utilized path planning based on level-set methods, and we implemented all of the available strategies for fast planning and re-planning. The method we employed is as fast as any planning method that operates over a quantized map. However, we found in practice that there were pathological cases where real-time planning constraints could not be met. As we began to investigate planning in larger areas, which required additional planning time, we realized that a fundamentally new and faster approach is required. Since our planning algorithms were already as fast as any available, our focus shifted from fast planning algorithms to sparse representations of the underlying map.

This year we have developed a new sparse topological representation of riverine environments, and we have integrated it with our guidance algorithms. The result is that we can compute global plans in real-time over areas that are significantly larger than was possible previously.

A topological map is built from a binary image, or a set of binary images, covering the entire operating area. Figure 1 shows satellite image and corresponding binary image of a typical riverine environment.

Figure 1. Satellite image and corresponding binary image of a typical riverine environment.

The topological map is extracted from the binary input image by first applying morphological thinning and distance transform operations to the image and then extracting topologically significant vertices from the resulting skeleton. Each vertex in the topological map represents a circular region that is safe for navigation. Edges in the map represent straight line paths that join adjacent circular navigable regions. Figure 2 shows the topological map obtained from the riverine environment in Figure 1, and Figure 3 shows circular regions at each vertex superimposed on the topological map. The union of all circular regions approximates the navigable areas in the entire environment. Figure 4 shows topological map along with the circular navigable regions around each vertex, superimposed on the satellite image of the environment.

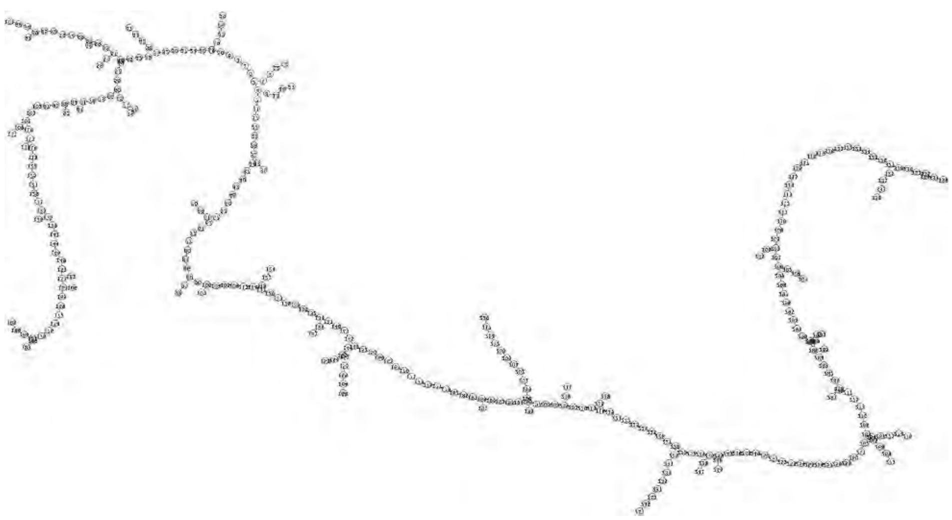

Figure 2. Topological map of riverine environment.

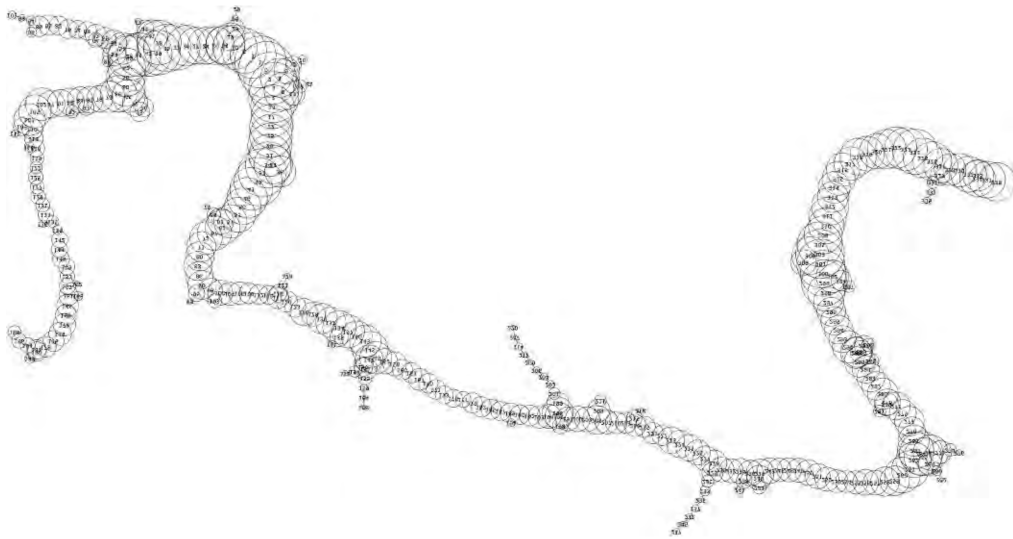

Figure 3*: *Topological map with superimposed navigable circular regions.

Figure 4. Topological map, with navigable circular regions, superimposed on satellite image of the environment.

The topological map for the environment in Figure 1 consists of about 350 vertices and edges. The environment is about 1500m x 2700m and a grid map representation would require more than 4 million grid cells at 1m resolution. As the environments get larger, advantages of compact representation offered by the topological map approach become more significant.

In practice, the global path does not need to be updated very often. In fact, we find that we can use very stale global data while retaining formal guarantees that a sequence of local dynamically feasible

trajectories will converge to the goal location. We use a formal test, described in Stilwell *et al*, 2011, to determine if the global path needs to be updated. If the formal test fails, the topological map needs to be repaired only locally by replacing parts of the topological map within the local region by a local topological map. Figure 5 shows an example of a repaired topological map. We note that the part of topological map (red curve) within the local region (red rectangle) is replaced with part of local topological map (blue curve) within the same region. This algorithm has been successfully implemented on VT USV and tested in field.

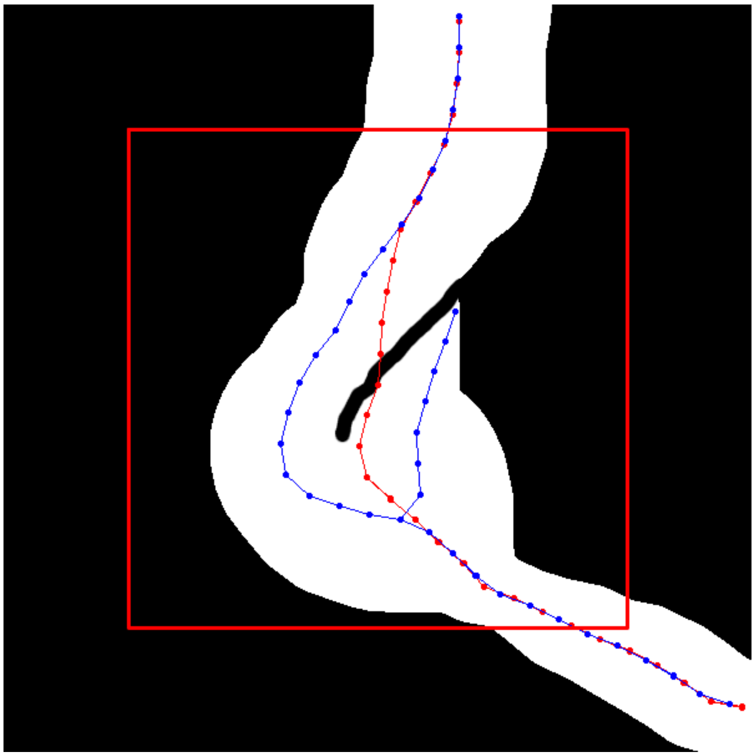

Figure 5. An a-priori topological map that is incorrect (red) and the corresponding repaired topological map (blue).

Generalized sonar

In order to integrate our autonomy and sensing package on an arbitrary small vessel, we have been developing a generalized sonar mount. At present, we have completed a detailed design of the sonar mount, and prepared machine drawings. Components are currently being fabricated, and the sonar mount will be assembled and tested within the next month. The generalized sonar mount is shown in Figure 6. In order to maximize vessel speed while the sonar mount is deployed, we have incorporated design features that reduce drag. The pole onto which the sonar is mounted has a wing-shaped fairing which reduces drag of the pole, and the motor that acuates the pan axis of the sonar head is located out of the water on the top of the pole.

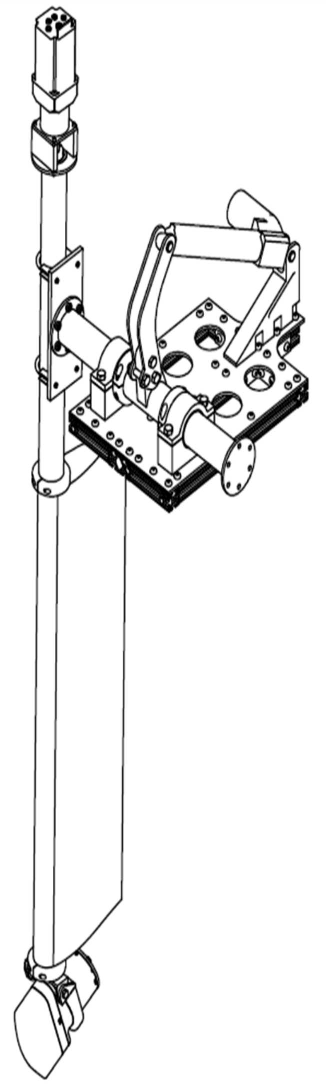

Figure 6. Sonar mount.

Riverine USV trajectory control using identified dynamic models

Activities have focused on developing a control architecture that enables the USV to track commanded trajectories in the presence of environmental disturbances and uncertainies in the dynamic model of the USV. Moreover, we seek to control the vessel through all of its operating envelope, including sternward motion.

The input to the control system is a desired trajectory. In our case, the desired trajectory is computed by the guidance system.   The control system has a hierarchical structure. At the top tier, errors in the crosstrack and downtrack directions drive inner-loop heading and speed control loops which generate steering and throttle commands for the USV.   The overall control architecture is shown in Figure 7. The trajectory controller can be used throughout the USV's performance envelope, including sternward motion.

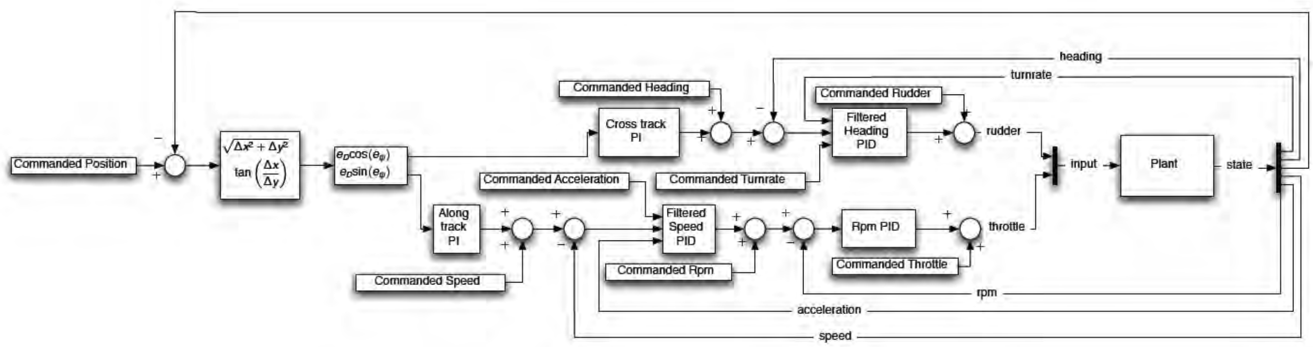

Figure 7. Cascading Trajectory Controller

The dynamics of sternward motion and forward motion are significantly different. Perhaps the most notable difference is that for most rudder angles, there are two corresponding steady-state turn rates. In other words, if the rudder is held constant, the USV can exhibit a steady turning motion to port or starboard, depending on initial conditions and environmental disturbances. The overall control law incorporates prior knowledge of the achievable steady, sternward motions along with feedback to improve the local performance in a neighborhood of the given steady motion.

Figure 8 shows the USV tracking a desired trajectory. The desired trajectory is shown in black, and all other lines are the acutal USV trajectory while tracking the desired trajectory during several experiments. Future efforts will include adaptively adjusting steady state behavior to account for configuration changes as well as adaptively adjusting to constant flow conditions.

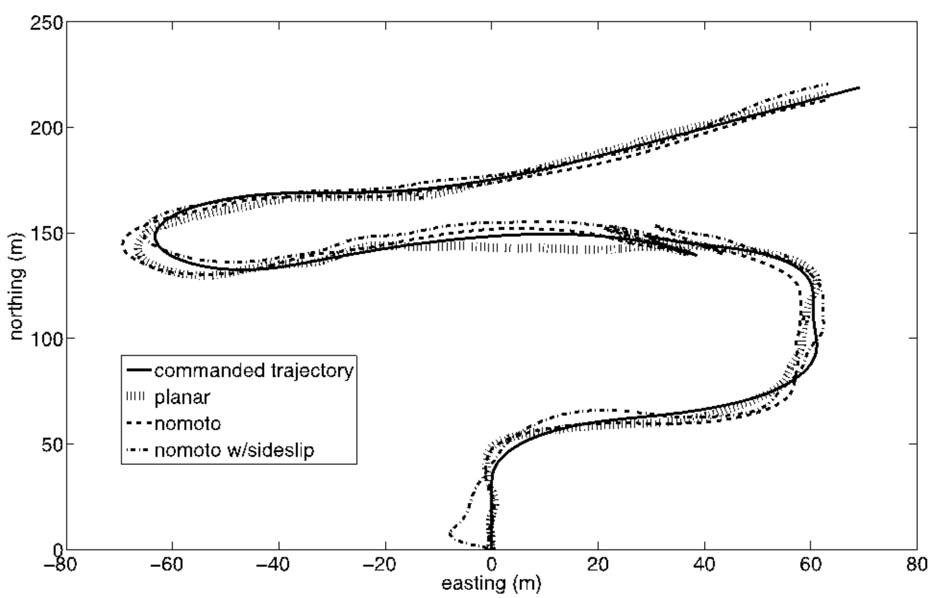

Figure 8: Trajectory control for three linear steering models and a linear Speed Model. The black line represents the desired trajectory, while the other lines represent the USV's trajectory while tracking the desired trajectory.

Trajectory generation that includes sternward motion
The USV must exhibit controlled sternward motion while operating in challenging riverine systems. We have developed an extension of our current trajectory generation algorithm that addresses sternward motion. The principal challenge of implementing a trajectory generation algorithm is the requreiment to meet real-time computational constraints. Adding sternward motion to the set ot potential solutions increases the dimension of the search space for the corresponding optimization problem, and increases the challenge of meeting real-time constraints.

We have developed a two-stage approach to generate trajectories that include sternward motion. First, we compute an optimal trajectory that consists of only forward motion. As with a human helmsman, we prefer to operate the vessel in forward motion. If all available forward trajectories are infeasible because they intersect a hazard to navitation, then we compute a trajectory that consists of a sternward motion segment followed by a forward motion segment. The time at which the USV switches from sternward motion to forward motion is a degree of freedom in the optimizaiton problem. Indeed, it is the only additional degree of freedom beyond what is already required by the trajectory generation algorithm that computes forward-only trajectories. Thus we are able to meet real-time computation constraints.

Our approach is illustrated in Figure 9. The red line represents the forward-only trajectory that intersects land and is therefore infeasible. The blue line indicates the successful trajectory that includes sternward and forward motion. Note that the USV needs only a short sternward segment before resuming forward motion. To date we have tested the new trajectory generator in simulation only.

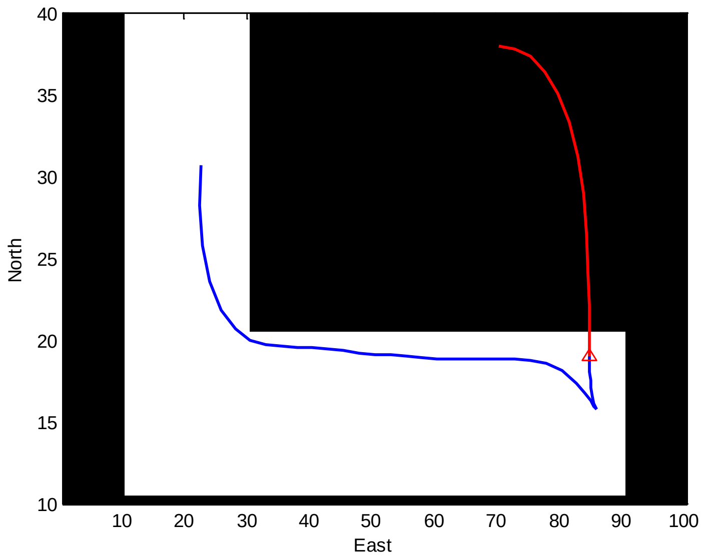

Figure 9*: *(blue) Trajectory with forward and sternward motion; (red) infeasible forward-only trajectory that intersects land.

IMPACT/APPLICATIONS

The principal result of this project will be a set of algorithms and best-practice tools for robust autonomous surface vehicle operations in dynamic and partially mapped riverine systems.

RELATED PROJECTS

None.

PUBLICATIONS

[1] A Wolek and CA Woolsey, 2012, Time-optimality versus disturbance rejection in Dubins path planning, in *Proc. American Control Conference*, Montréal, Canada. [submitted, refereed]

[2] C Sonnenburg and CA Woolsey, 2012, Riverine USV system identification and trajectory control, in *Proc. American Control Conference*, Montréal, Canada. [submitted, refereed]

[3] CA Woolsey, Vehicle dynamics in currents, VaCAS Technical Report No. VaCAS-2011-01, September 2011. [published]

[4] A Gadre, S Du, DJ Stilwell, 2011, A Topological map based approach to long range operation of an unmanned surface vehicle, in *Proc. American Control Conference*, Montréal, Canada. [submitted, refereed]

[5] DJ Stilwell, A Gadre, AJ Kurdila, 2011, A Receding horizon approach to generating dynamically feasible plans for vehicles that operate over large areas, *in Proc. IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems*, San Francisco, CA. [published, refereed]